# The Cambridge-Cambridge ROSAT Serendipity Survey - III. VLA observations and the evolution of radio-quiet and radio-loud objects

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# The Cambridge-Cambridge *ROSAT* Serendipity Survey - III. VLA observations and the evolution of Radio-quiet and Radio-loud objects

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**ABSTRACT**

We present the results of the VLA Radio observations at 1.475 GHz (20 cm) of the Active Galactic Nuclei (AGN) in the Cambridge-Cambridge *ROSAT* Serendipity Survey (CRSS), a sample of 123 faint X-ray sources with $f_x$(0.5-2.0 keV)$\geq 2 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$. Of the 80 AGN in the sample, seven show radio emission at 5 $\sigma$ level and only two ($2.5^{+4.0}_{-1.7}$ %) qualify as Radio-Loud (RL) objects ($\alpha_{ro} \geq$0.35). This result, compared with 13% RL in the *Einstein Observatory* Extended Medium Sensitivity Survey (EMSS) sample of AGN (flux limit $f_x$(0.3-3.5 keV)$\sim 2 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$) confirms that the fraction of X-ray selected RL AGN drops rapidly as the X-ray flux limit is lowered.

Combining the CRSS AGN sample with that extracted from the EMSS we have studied the X-ray Luminosity Function (XLF) and evolutionary properties for Radio-Quiet (RQ) and Radio-Loud separately. We find that the RQ and RL AGN population show the same cosmological evolution within the errors. In fact, when the luminosity evolution is parameterised with a power law of the form $L_X^*(z) = L_X^*(0)(1+z)^k$, we find $k = 2.43 \pm 0.26$ and $k = 2.71 \pm 0.10$ for RL and RQ AGN populations respectively. In addition, the shape of the de-evolved XLF of the two classes appears to be different both at the low luminosity ($L_X < 10^{44}$ erg s$^{-1}$) and high luminosity ends. These results are robust for different cosmological models (using q$_0$=0.0 and q$_0$=0.5) and for different value of the threshold $\alpha_{ro}$ used to distinguish between RQ and RL objects.

Finally we find that the differences in the shape of the XLF of RQ and RL AGN can be explained by introducing an X-ray beaming model to separate the observed X-ray luminosity of radio quasars into relativistically beamed and isotropic contributions.

**Key words:** galaxies:active – galaxies:nuclei – quasars:general – radio continuum: galaxies – X-ray: galaxies

## 1 INTRODUCTION

The cause of the difference between AGN that are strong radio sources (radio-loud, RL) and those which are radio-quiet (RQ) is one of the most basic topics in the field of quasar astronomy. Although the two classes have similar spectral distributions (SEDs) outside the radio band (Elvis et al. 1994), their luminosity functions show differences in all the bands in which they have been studied.

In the optical band, using the PG sample of optically selected AGN (Schmidt and Green, 1983), Padovani (1993) has shown that the shapes of the luminosity functions for RL and RQ are different. As a result of these differences, the fraction of radio-loud objects is ~20-50% for $M_B \leq -24.5$, but falls to 7-8% at fainter absolute magnitudes.

Recently, Della Ceca et al. (1994, hereafter DC94) using the *Einstein Observatory* Extended Medium Sensitivity Survey (EMSS, see Gioia et al., 1990 and Stocke et al. 1991) sample of X-ray selected AGN, have determined the X-ray luminosity functions (XLF) of RL and RQ separately. They have obtained results very similar to those obtained by Padovani (1993) in the optical domain. The shape of the XLF of the two classes appears to be different and a flattening of the XLF of the RL sample is visible for $L_x \leq 10^{44.5}$ erg s$^{-1}$. As a result of this difference the expected fraction of RL is a function of the X-ray flux limit in X-ray surveys. They predict that this fraction is $\sim$13 % for $f_x \sim 2 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ and decreases to $\sim$ 2.5 % for $f_x \sim 2 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$.

Until recently the EMSS AGN sample was the only sample of X-ray selected AGN for which complete radio information exists. Now a new, fainter sample of X-ray selected AGN has been obtained using the *ROSAT* satellite. This new sample, the Cambridge-Cambridge *ROSAT* Serendipity Survey (CRSS, Boyle et al. 1995) is a well defined sample of 80 X-ray selected AGN discovered serendipitously in 20 ROSAT PSPC fields at high Galactic latitude ($|b^{II}| \geq 30°$). The selection criteria were: an X-ray flux $f_x$(0.5-2.0 keV)$\geq 2 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ (some 10 times fainter than the typical EMSS limit), and an off-axis angle $\theta \leq 15'$ in the PSPC field. Of the 80 sources, 68 were classified as QSOs from the presence of broad emission lines (full width half maximum (FWHM) > 1000 km s$^{-1}$), while 12 were classified as narrow emission line X-ray galaxies (NLXGs) (see Boyle et al. 1995 for more details). A full description of the sample will appear elsewhere (McMahon et al. 1995, in preparation).

In this paper we report the results of VLA† observations of all 80 sources in the CRSS AGN sample. Our aim was to obtain a complete classification of the sample members as RL or RQ in order to determine well-constrained XLFs for X-ray selected RQ and RL AGN separately.

The paper is organized as follows. In Section 2 we describe our radio observations of the CRSS sample. We present the results of these observations in Section 3, while in Section 4 we report the X-ray luminosity function of RQ and RL objects. Finally we present our conclusions in Section 5. Throughout the paper a Hubble constant of 50 km s$^{-1}$ Mpc$^{-1}$ is assumed.

## 2 VLA DATA

We observed 18 of the 20 fields of the CRSS sample with the National Radio Astronomy Observatory (NRAO) Very Large Array at a frequency of 1.475 GHz (20 cm) on 5 June 1994. The observing bandwidth was 25 MHz in the B configuration. This combination of frequency, bandwidth and configuration allows us to obtain a primary beam of full width half power (FWHP)$\simeq 30'$. The sensitivity of the VLA decreases radially compared with the value at the centre of the primary beam such that it decrease to $\sim$0.5 and $\sim$0.2 of its peak value at off-axis angles of $\theta \simeq 8'$ and $\theta \simeq 25'$ respectively. The synthesized beamwidth was 3.9$''$ FWHP. Because the primary beam has about the same size as the region of the *ROSAT/PSPC* from which the X-ray sources were extracted, in general we obtained one VLA observation for each *ROSAT/PSPC* field. However the VLA pointing position was not simply made coincident with the *ROSAT* central field position but was chosen instead to minimize the off-axis angle of the X-ray sources within the radio field of view. For one field (NGC5907, ror=WP600190) it was necessary to carry out two different VLA pointings, so we have carried out a total of 19 pointings.

Since our aim was a complete classification of the CRSS sources into RL or RQ objects, we set the integration time to ensure a clean discrimination between RL and RQ for undetected objects. From Zamorani et al. (1981) a quasar is defined as radio-loud when the radio to optical spectral index, $\alpha_{ro} \geq$0.35 where $\alpha_{ro}$=$-$log(L$_{2500\ \text{Å}}$/L$_{5\ \text{GHz}}$)/5.38. Using the redshifts and optical (POSS) magnitudes of each object from McMahon et al. (1995), we calculated the radio flux at 1.475 GHz needed to detect a source with $\alpha_{ro}$=0.35. Because $\alpha_{ro}$ is computed between 2500Å (assuming $\alpha_o$=1.0) and 5 GHz (rest frame), we have assumed a spectral slope $\alpha_r$=0.7 ($f_\nu \propto \nu^{-\alpha_r}$ Zamorani et al. 1981) to calculate the radio flux at 1.5 GHz in the observed rest frame. The flux limits do not change significantly if we assume a flatter radio spectral index (for example $\alpha_r$=0.3). Allowing for the loss of sensitivity for off-axis sources, we derived integration times between 5 and 20 minutes. All the observations were interspersed with nearby calibrator observations at 20 minute intervals. The primary flux density calibrator was 3C48 which was assumed to have a flux density of 15.59 Jy.

For the two remaining fields, PG1512 (ror=RP700807) and 4U1417+42 (ror=WP700535) radio data were available in the literature or from the VLA archive. The *ROSAT PSPC* field 4U1417+42 is centered on the BL Lac object 1426+4253. This object was observed by Dr. M. Marcha and collaborators with the VLA on 1991, at 20 cm, configuration B, bandwidth 50 MHz with an integration time of 20 minutes (VLA archive code: AM330). The *ROSAT PSPC* field PG1512 is centered on the quasar 3C351. From the VLA archive we retrieved the observation obtained by Dr. J.P. Leahy in 1987, at 20 cm, B configuration, bandwidth 25 MHz and with an integration time of 55 minutes (VLA archive code: AL146). The source CRSS1620.1+1724 was observed by Kellermann et al. (1989) with the VLA at 5 GHz (6 cm), D configuration, bandwidth 50 MHz.
Altogether we have VLA data for all 80 AGN in the CRSS sample (72 from our observations, 7 from the VLA archive and 1 from the literature).

## 3 RESULTS

Each field was analysed with the NRAO AIPS reduction package. We searched for radio sources above the 5$\sigma$ local r.m.s. noise at the optical position of each source. Because both optical and radio positions have an error of $\sim 1''$, we searched for radio sources inside a circle of 5$''$ radius centered on the optical position of each AGN to permit also the detection of possible double radio sources. Whenever a radio source at the 5$\sigma$ level was found within this circle its peak flux density was taken to be the radio flux density of the AGN. When no radio source was detected, we determined a 5$\sigma$ upper limit at the optical position. All flux densities were corrected for primary beam attenuation.

† The Very Large Array (VLA) is a facility of the National Radio Astronomy Observatory (NRAO) which is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

Of the 80 CRSS X-ray selected AGN, 6 were detected from our observations at 1.475 GHz with fluxes ranging from 0.44 to 6.85 mJy and one (CRSS1620.1+1724) was detected at 5 GHz with a flux of 1.09 mJy (Kellermann et al. 1989). Of these, 6 are QSOs and one is an NLXG. The differences between the radio and optical positions for the radio detections ranges from $0''$ to $1.47''$. All detected sources were the only radio sources down to 3 $\sigma$ within $5''$ radius of the optical position. Most of the 5 $\sigma$ upper limits are in the range 0.25-1.00 mJy. Only in few case did the presence of a strong (> 1 Jy at 20 cm) radio source in the field results in higher upper limits, typically 3-5 mJy, except for one case (CRSS1418.3+0637) where we have a 5 $\sigma$ upper limit of 25 mJy. The radio data on the 80 AGN in the CRSS sample are given in Table 1.

The X-ray flux of each object was obtained by analysing all the X-ray sources with the IRAF/PROS‡ software package. A full description of the X-ray spectral analysis and X-ray flux list will appear elsewhere (Ciliegi et al. 1995, in preparation). The B magnitude of each object was estimated from the $O$ mag. and $O - E$ color using (Evans 1988):

$$B = O - 0.119(O - E)$$

The optical luminosity at 2500Å and the radio luminosity at 5 GHz were computed following Zamorani et al. (1981):

$$\log L_{2500\ \mathrm{Å}} = 38.011 - 0.4B + 2\log(z(1+z/2))$$
$$\log L_{5\ \mathrm{GHz}} = 34.63 + \log S(\nu) + 2\log(z(1+z/2)) + \alpha_r \log\frac{\nu}{5000} + (\alpha_r - 1)\log(1+z)$$

where $S(\nu)$ is the observed radio flux (in Jy) at frequency $\nu$ in MHz ($\nu$=1.475 GHz in our observations) and $\alpha_r$ is the energy slope measured at radio wavelengths. Following Zamorani et al. (1981) we have assumed $\alpha_r$=0.7.

In Figure 1, we show $\alpha_{ox}$ vs. $\alpha_{ro}$ for all the sources of the CRSS sample. The dashed line represents the division between radio-loud ($\alpha_{ro} \geq 0.35$) and radio-quiet ($\alpha_{ro} < 0.35$) objects. Different symbols were used to distinguish between QSO (open) and NLXG (filled) and between radio detections (circles) and radio upper limits. Only two QSOs (CRSS1705.5+6042 and CRSS2250.0+1407, see Table 1) have $\alpha_{ro} \geq 0.35$ and these only slightly so. These two objects remain the only objects with $\alpha_{ro} \geq 0.35$, also assuming a flatter radio spectral index ($\alpha_r$=0.3) to derive the radio luminosity. The number of RL objects in the CRSS sample depends on the chosen $\alpha_{ro}$ threshold. This dependence is discussed in §4.2.

## 4 THE X-RAY LUMINOSITY FUNCTION

### 4.1 *4.1 The X-ray Luminosity Function of RL and RQ AGN*

In order to determine well-constrained XLFs for X-ray selected RQ and RL AGN separately, we have combined the CRSS data with the EMSS data. Following DC94, we have used only the portion of the EMSS north of $-40°$ declination and we have considered as RQ those objects with a radio upper limit $\alpha_{ro} \geq 0.35$. With these choices, the RL AGN sample consists of 45 objects (43 from EMSS and 2 from CRSS) while the RQ sample consists of 440 objects (363 from EMSS and 77 from CRSS). These numbers show that the fraction of RL AGN in the CRSS sample ($\sim 2.5^{+4.0}_{-1.7}$%) is lower than the fraction of RL AGN in the EMSS sample (∼13%). This is in agreement with the prediction of DC94 that the expected fraction of RL should drop rapidly as the X-ray flux limit is lowered (the X-ray flux limit for the CRSS sample is $f_x$(0.5-2.0 keV)$\sim 2 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$, some 10 times fainter than the typical EMSS limit).

The RQ object CRSS1620.1+1724 was excluded from the CRSS sample because it is in common with the EMSS sample (MS1617.9+1731). The 0.5-2.0 keV X-ray fluxes of the CRSS sample were converted to the EMSS 0.3-3.5 keV passband using S(0.3-3.5 keV) = 1.8 S(0.5-2.0 keV) which is accurate to 2% for spectra with spectral indices in the range $0.6 < \alpha_x < 1.5$ (Boyle et al. 1993). Throughout this paper, in order to maintain consistency with the analysis of DC94, we have assumed $\alpha_x = 1.0$.

Using the $V_e/V_a$ variable of the $1/V_a$ method of Avni and Bahcall (1981), DC94 have shown that in both the RL and RQ sample the hypothesis of no evolution is rejected at more than the 99.99% confidence level. We have repeated the same analysis, combining CRSS and EMSS sample, with the same result. Having confirmed that both RL and RQ samples exhibit significant cosmological evolution, we then used the maximum likelihood technique to obtain a "best-fit" parametric representation for the luminosity function and its evolution for both samples (see Boyle et al. 1993 and Marshall et al. 1984 for a complete description of this method). As in Boyle et al. 1993, we use the two-power-law form for the XLF

$$\Phi_X(L_X) = \Phi^*_X L_{X_{44}}^{-\gamma_1} \qquad L_X < L^*_X(z=0)$$

$$\Phi_X(L_X) = \frac{\Phi^*_X}{L_{X_{44}}^{(\gamma_1-\gamma_2)}} \; L_{X_{44}}^{-\gamma_2} \qquad L_X > L^*_X(z=0)$$

where $\Phi^*_X$ is the normalization of the XLF and $\gamma_1$ and $\gamma_2$ are the faint and bright end slopes respectively. $L_{X_{44}}$ is the 0.3-3.5 keV X-ray luminosity expressed in units of $10^{44}$ erg s$^{-1}$.

To study the evolutionary properties of RQ and RL samples we have used a (1+z) power-law evolution in the "break" luminosity, $L^*_X(z)$ (Boyle et al. 1993):

$$L^*_X(z) = L^*_X(0)(1+z)^k$$

Since the maximum-likelihood analysis only give a "best-fit" solution without information on a "goodness of fit" for the best-fit model, we must also test for the acceptability of the model against the data. To do this, we used the 2-dimensional KS statistic (Peacock 1985) employing the algorithm devised by Press et al. (1992). This statistic produces a probability $P_{KS}$ for the model being an acceptable fit to the data. A 2D KS test shows that the power-law evolutionary form that we have used in our analysis, is an acceptable fit to the data, with a KS probability always greater than 10 per cent.

Because DC94 in their analysis used a different method to study the evolutionary properties, as first step we applied the method just to the EMSS data for RL and RQ separately (model A and B for $q_0$=0.0 and $q_0$=0.5 respectively). The

‡ IRAF is distributed by NOAO, which is operated by AURA, Inc., under contract to the NSF.

results of the $V_e/V_a$ test, maximum likelihood analysis and 2D KS test are presented in Table 2. The quoted errors are at $1\sigma$ level, determined using the method described by Boyle, Shanks and Peterson (1988). Table 2 shows that the evolutionary parameters obtained with our analysis are in good agreement with the results obtained by DC94 ($k = 2.35^{+0.22}_{-0.25}$ and $k = 2.92^{+0.19}_{-0.23}$ at $1\sigma$ level for RQ and RL respectively). The small discrepancies between the "best-fitting" parameter values derived with the maximum-likelihood method and those obtained with the method used by DC94 must be simply due to the different analysis methods applied (Boyle et al. 1993). The significant difference in $\gamma_1$ (the faint end slope of the XLF) between RL and RQ, confirms the flattening of the XLF of the RL sample for $L_X(z=0) \leq 10^{44.5}$ erg s$^{-1}$ noted by DC94.

We then combined EMSS and CRSS samples (model C ($q_0$=0.0) and D ($q_0$=0.5)). The inclusion of the CRSS does not change the value of the evolution parameter $k$ significantly. However, we note an increase of $k$ for RQ AGN and a decrease for RL AGN. An increase of the evolution parameter of the same order of magnitude ($\Delta k \sim 0.2$) was found by Boyle et al. 1993, when combining the EMSS and the *ROSAT Deep* Survey. For the CRSS sample, this difference in the evolution parameter may be explained in terms of the difference in the mean spectral index between the CRSS and EMSS samples. The spectral index $\alpha_x$ enters straightforwardly into the determination of the evolution parameter $k$ in the power-law evolution model (Della Ceca et al. 1992). If $k'$ is the derived value for the evolution paramenter in the case where $\alpha_x = 1.0$, then $k = k' + (\alpha_x - 1)$. Because the mean spectral index of the CRSS sample is $\alpha_x = 1.2$ (Ciliegi et al. 1995 in preparation) while the mean spectral index of the EMSS sample is $\alpha_x = 1.0$ (Maccacaro et al. 1988), we have a difference between the two samples of $\Delta\alpha \simeq 0.2$. Although the combined sample (EMSS + CRSS) of RQ AGN is strongly dominated by the EMSS sources ($\sim$80%), the fact that we found $\Delta k \simeq \Delta\alpha_x$ (see models A and C in Table 2) suggests that the difference in the evolution parameter simply reflects the difference in the mean spectral index of the two samples. This difference may be real, reflecting a "soft excess" in the *ROSAT/PSPC* band ($\sim$0.1-2.4 keV) compared to the *Einstein* IPC band ($\sim$0.3-3.5 keV), or may be due to calibration error in the PSPC and/or IPC instruments (see Appendix B in Fiore et al. 1994 for more details). We conclude that the differences in the evolution parameter between RL and RQ AGN are within the $1\sigma$ error in all the models that we have analyzed. Therefore, with the available data we do not find evidence that the cosmological evolution of RL and RQ AGN is different.

It is, however, clear that the shape of the XLF is different for RL and RQ objects also using different cosmological model ($q_0$=0.0 and $q_0$=0.5). Table 2 shows that in model C and D the values of $\gamma_1$ and $\gamma_2$ are significantly different for RL and RQ AGN. The shape of the XLF is different not only at low luminosity as noted by DC94, but also at the bright end. In Figure 2 we plot a de-evolved z=0 XLF obtained with the maximum likelihood analysis for the EMSS and for the combined (EMSS + CRSS) samples (models A and C respectively). To test if this behaviour of the XLF is due to an error in the X-ray flux calibration of the CRSS sources we have calculated the XLF (for $q_0$=0.0) increasing and decreasing the X-ray flux of the CRSS sources by 30% respectively. The RL and RQ evolution parameters are still equal within their $1\sigma$ errors, while the difference in the shape of RQ and RL XLF ($\gamma_1$ and $\gamma_2$ parameters) remains significant.

## 4.2 Dependence of the XLF of RQ and RL on the definition of Radio-loudness

Until now, we have used the value $\alpha_{ro}$=0.35 to discriminate between RL and RQ objects. This value represents a natural division of X-ray selected AGN in RQ and RL. In fact, as shown by DC94, the $\alpha_{ro}$ distribution of EMSS AGN is a clear bimodal distribution with a minimum at $\alpha_{ro} \simeq 0.34$ - 0.37 (see Figure 3a). It is clear in Figure 3b that the addition of the CRSS sample does not change this. The combined $\alpha_{ro}$ distribution has still a bimodal distribution with a minimum at $\alpha_{ro} \simeq$0.35. However, other authors have used different values of $\alpha_{ro}$ to discriminate between RL and RQ, testifying to the fact that the underlying physical differences between the two classes are not well understood. For example, Stocke et al. (1992), studying optically selected samples of quasar, concluded that the most likely dividing value between the RQ and RL populations is $\alpha_{ro} \sim$0.20.

To test whether our results depend on the value of $\alpha_{ro}$ chosen to separate RQ from RL, we have re-calculated the XLF for RQ and RL using different values of $\alpha_{ro}$. In table 2 we report (models E to G) the "best-fit" parameters for RQ and RL XLF using $\alpha_{ro} = 0.2$, 0.4 and 0.5. When we use $\alpha_{ro}$=0.20 (model E), some sources have inadequate radio upper limits ($\alpha_{ro} \geq$0.20). We assumed all these (108 sources in the EMSS sample and 36 in the CRSS sample) to be RQ AGNs in models E and to be RL AGNs in model E$'$. In Figure 4 we show the de-evolved z=0 XLF for models E to G. The shape of the RL and RQ XLFs remains significantly different for all values of $\alpha_{ro}$. In the $\alpha_{ro}$=0.2 models, the difference is only marginal if we assume that all the sources with inadequate upper limits are RQ AGNs (model E) and disappears if we assume all these sources to be RL AGNs (in model E$'$ the parameters $\gamma_1$ $\gamma_2$ and log$L^*_X$ are all consistent within the $1\sigma$ errors). However these models are unrealistic due to the simplifying assumption that all the sources with a radio upper limit $\alpha_{ro} \geq$0.20 are RQ or RL AGNs (we expect that only about 13% ($\sim$ 20 objects) of these sources are RL AGN).

The major effect of changing the threshold $\alpha_{ro}$ on the XLF is on the faint end slope of the XLF for RL AGN (see parameter $\gamma_1$ in Table 2 for models E - G). An increase in the $\alpha_{ro}$ threshold results in the loss of the faintest bin in the RL XLF (Figure 4). This is due to the strong correlation between $\alpha_{ro}$ and the X-ray luminosity (Figure 5) first noted by Zamorani et al. (1981) for radio and optically selected QSOs. Increasing the threshold $\alpha_{ro}$ (dotted lines in the top panel of Figure 5) excludes mainly objects with low X-ray luminosity.

Changing the threshold $\alpha_{ro}$ does not affect the evolution parameter $k$: the two populations of objects show the same cosmological evolution in all the models that we have analysed. Therefore the conclusion that RQ and RL AGN show the same cosmological evolution and have different shapes of their XLFs, is robust to changes in the cosmological model used (models A - D), and to the value of $\alpha_{ro}$

used to discriminate between RL and RQ objects (models E - G).

### 4.3 The different shape of RQ and RL XLF : a possible explanation

We now investigate how the different shapes of the RQ and RL XLFs could arise from the RL objects having an additional mechanism producing X-rays.

The difference between RL and RQ AGN in the X-ray band have been studied by many authors. Zamorani et al. (1981) showed that, for a given optical luminosity, the X-ray luminosity of RL is $\sim$ 3 times stronger than for RQ. This property is clearly present in Figure 5. Worrall et al. (1987) confirmed this property and showed that, for a given optical luminosity, the X-ray emission is expected to be higher for RL AGN with flat radio spectra (that is, with a dominant compact radio emission) than for RL AGN with steep radio spectra. Also the shape of the X-ray spectra appear to be different in RL and RQ. Wilkes and Elvis (1987) showed that RL objects have flatter X-ray spectra ($\alpha_x \sim$0.5 in the 0.3-3.5 keV band) compared to RQ objects ($\alpha_x \sim$1.0). Lawson et al. (1992), using EXOSAT data, showed that RL objects have X-ray spectral indices consistent with a unique index (i.e. consistent with a dispersion $\sigma$=0.0), whereas RQ objects show a large spread in indices ($\sigma >$0.10)

All these differences between RQ and RL AGN can be explained if we consider a simple two component scenario for quasar X-ray emission. In this scenario (first proposed by Zamorani et al. 1981) all quasars have a central "energy machine" which provides at least part of the optical and X-ray emission. Any mechanism proposed to explain this emission should contain one or more variable parameters which can produce the large observed dispersion in the X-ray luminosities (Figure 5), in the level of X-ray loudness ($\alpha_{ox}$, Zamorani et al. 1981), and in the X-ray spectral indices of RQ AGN (Lawson et al. 1992). In addition, RL quasars must have a second X-ray producing mechanism to explain their higher observed average ratio between X-ray and optical luminosity, the lack of RL objects with low X-ray luminosity (see Figure 5), the flatter X-ray spectra of RL AGN (Wilkes and Elvis 1987) and the low dispersion in the X-ray spectral indices of RL AGN (Lawson et al. 1992).

In the framework of the "unified interpretation" for RL AGN (Blandford and Königl 1979), the differences between radio core-dominated (CDQs) and lobe-dominated quasars (LDQs) are due to orientation alone. Based on the correlation of the X-ray luminosity with nuclear and lobe radio luminosity (Worrall et al. 1987, Browne and Murphy 1987) and on the fact that soft X-ray energy indicies have been found to be systematically flatter for CDQs than for LDQs (Canizares and White 1989, Boroson 1989, Shastri 1991), Shastri (1991) suggested that the "radio-linked" component of the X-ray emission in RL AGN is orientation-dependent and relativistically beamed.

In the past years, several authors developed models to explain this scenario (Kembhavi, Feigelson and Singh 1986, Browne and Murphy 1987, Kembhavi 1993). The general feature of these models is that the two components of the X-ray emission mentioned above have the following properties: (a) the first component unrelated to the radio emission (the "radio-quiet mechanism") is intrinsically very dominant and has a steep X-ray spectrum with $\alpha_x \sim$1.0 (b) the additional component in RL quasar associated with the radio emission (the "radio-linked mechanism") has a flat X-ray spectrum ($\alpha_x \sim$0.5) and, although intrinsically weak relative to the other component, it makes a significant contribution to the X-ray emission due to the effect of relativistic beaming when the direction of the jet with which it is associated is oriented close to the line of sight.

In this "X-ray beaming" model, the total X-ray luminosity $L_x$ of RL AGN can be written as:

$$L_x = L_{xb} + L_{xu}$$

where $L_{xu}$ is the unbeamed X-ray luminosity associated with the radio-quiet mechanism which occurs in both RQ and RL and $L_{xb}$ is the beamed X-ray luminosity which is dominant in core-dominated RL due the beaming effect. In this scenario we do not expect to have different shapes of the XLF for RQ AGN and RL AGN, if for the latter we use only the unbeamed luminosity.

If we call $F$ the ratio of the beamed X-ray component to the isotropic component

$$F = \frac{L_{xb}}{L_{xu}}$$

the beamed and unbeamed X-ray luminosity are:

$$L_{xb} = \frac{L_x\ F}{1+F} \qquad \text{and} \qquad L_{xu} = \frac{L_x}{1+F}$$

In this model the radio luminosity from extended radio regions in quasars is unbeamed ($L_{ru}$) and has a steep radio spectrum, while that from the compact region has a flat spectrum and is boosted due to the relativistic motion of the emitting region. The observed compact radio luminosity can be written as $L_{rb}(\theta) = L_{rb}(90^\circ)g_r(\beta,\theta)$ where $L_{rb}(90^\circ)$ is the luminosity when the angle $\theta$ with the line of sight is $90^\circ$ and $g_r(\beta,\theta)$ is the beaming factor defined as

$$g_r(\beta,\theta) = \tfrac{1}{2}[(1-\beta cos\theta)^{-(2+\alpha_r)} + (1+\beta cos\theta)^{-(2+\alpha_r)}]$$

where v=c$\beta$ is the bulk velocity and $\alpha_r$ is the radio spectral index. For a given radio quasar, the radio beamed and unbeamed luminosity are observables. Assuming that the beamed X-rays arise in the compact radio source, which is also the source of the beamed radio radiation, then it is possible to obtain the X-ray beaming factor $g_x$ (which is defined in the same way as the radio beaming factor $g_r$ with $\alpha_r$ replaced by the X-ray spectral index $\alpha_x$) and hence the factor $F$ for the X-ray emission (see Kembhavi 1993 for more details).

Unfortunately we do not have good enough radio data to estimate $F$. However we can use the relation between $F$ and $L_x$ (found by Kembhavi 1993) to estimate the factor $F$ and then the unbeamed X-ray luminosity for each RL AGN in our sample. We have used the relation

$$\mathrm{Log}L_x = 0.124\times\mathrm{Log}(L_{xb}/L_{xu}) + 27.71 \qquad (1)$$

to obtain the unbeamed X-ray luminosity of each RL AGN. In this relation $L_x$ is the monochromatic luminosity at 2keV in units of erg s$^{-1}$ Hz$^{-1}$. [§]

[§] In Kembhavi (1993) it is reported the relation Log$L_x$ = 0.124$\times$Log$(L_{xb}/L_{xu})$ + 20.71 with $L_x$ monochromatic luminosity at 2 keV in units of erg s$^{-1}$ Hz$^{-1}$. He used a sample of 126 radio quasars obtained by Browne and Murphy (1987) for which pub-

Using $L_{xu}$ we have re-calculated the XLF for RL AGN. The "best-fit" parameters for this "unbeamed" XLF are reported in Table 2 under the model C$^{\star}$. A comparison of model C$^{\star}$ with model C-RQ shows that the two XLFs now have the same slope at the bright end ($\gamma_2$ parameter) while remain some differences at the faint end, although now the $\gamma_1$ parameters are consistent at less than $2\sigma$ level.

Because the Log$L_x$ - Log$F$ relation shows a large scatter (see Kembhavi 1993) and the author did not report the errors on the correlation coefficients, we have also investigated the effect on the unbeamed XLF for RL AGN using relations between Log$L_x$ and Log$F$ slightly different from that shown above. We find, for example, that for

$$\mathrm{Log}L_x = 0.13\times\mathrm{Log}(L_{xb}/L_{xu}) + 27.52 \quad (2)$$

the unbeamed XLF for RL AGN and the XLF for RQ AGN have the same shape. The "best-fit" parameter for this second unbeamed XLF for RL AGN are reported in Table 2 under the model C$^{\star\star}$. A comparison of model C$^{\star\star}$ with model C-RQ shows that the parameters $\gamma_1$ and $\gamma_2$ are consistent within the $1\sigma$ errors and that also the evolution parameters $k$ are consistent within the errors. The de-evolved z=0 XLF for RQ AGN (model C) and for unbeamed RL AGN (model C$^{\star\star}$) is plotted in Figure 6.

Using the relation (2) we find that the RL AGN in our sample show a large range in the factor $F$, and that only for four objects does the beamed X-ray luminosity give a significant contribution to the total X-ray luminosity. There are only four objects with Log$F$ >1. In table 3 we report the properties of these four objects. On the basis of the X-ray beaming model and on the relation between radio and X-ray emission, we expect that these sources are AGNs with flat radio spectra and with a dominant compact radio emission. The available radio data show that two of these sources are indeed core-dominated radio sources with flat radio spectra. MS0038.8−0159 (4C 02.04) is a core-dominated radio source with a radio spectral index $\alpha_r$=0.04 between 6 and 20 cm (Perley 1982), while MS2134.0+0028 (PKS2134+004) is a well known optically violently variable (OVV) core-dominated radio source (Murphy, Browne and Perley 1993, Browne and Perley 1986). Moreover, in the framework of the Synchrotron Self-Compton model, Ghisellini et al. (1993) derived for MS2134.0+0028 a very small angle ($\phi = 0.1°$) between the axis of the jet and the line of sight. For the other two sources MS0012.5−0024 and MS2247.8−0703 the only radio information are from the VLA snapshot observations at 6 cm (Stocke et al. 1991) with no information on the nature of these radio sources.

The change in the XLF that we have obtained by introducing the X-ray beaming model is due to these four objects. Because of their large value of $F$, these objects are shifted from the XLF bright bins to the fainter bins, causing a large change in the XLF due to the poor statistics (there are only one and three objects in the two fainter bins of the RL AGN XLF shown in lower panel of Figure 2).

Therefore, we can conclude that the differences in the shape of XLF between RQ and RL AGN can be explained introducing the X-ray beaming model where the "radio-linked" component in RL objects is orientation-dependent, but larger samples of X-ray selected AGN are needed to strengthen this conclusion.

## 5 CONCLUSION

Using the Very Large Array (VLA) we have obtained sensitive radio observations for all 80 X-ray selected AGN in the Cambridge-Cambridge *ROSAT* Survey. Seven of these sources show radio emission at $5\sigma$ level. Only two AGN qualify marginally as radio-loud on a standard radio to optical spectral index criterion. These two objects represent only $2.5^{+4.0}_{-1.7}$ per cent of the sample compared with 13% RL in the EMSS (flux limit $f_x$(0.3-3.5 keV)$\sim 2\times10^{-13}$ erg s$^{-1}$ cm$^{-2}$ ), confirming the prediction of Della Ceca et al. 1994 that the expected fraction of X-ray selected RL AGN should drop rapidly as the X-ray flux limit is lowered (the CRSS flux limit is $f_x$(0.5-2.0 keV)$\sim 2\times10^{-14}$ erg s$^{-1}$ cm$^{-2}$)

We have combined the CRSS sample with the EMSS sample and studied the X-ray luminosity functions for RQ and RL separately using the maximum likelihood method. To study the evolutionary properties of RQ and RL samples, we have used a power law evolutionary form $L^*_X(z) = L^*_X(0)(1+z)^k$. From our analysis we found that the RQ and RL populations show the same cosmological evolution. Using the best-fit evolution parameters we have computed the de-evolved X-ray luminosity function of RQ and RL AGN. The shapes of the de-evolved XLF of the two classes appear to be different both in their low luminosity and high luminosity slopes.

These results are robust against: (i) possible errors due to the calculation of the ROSAT X-ray flux (increasing and decreasing the flux of the CRSS sources of 30%); (ii) for different cosmological models (using $q_0$=0.0 and $q_0$=0.5); (iii) for different value of the threshold $\alpha_{ro}$ used to distinguish between RQ and RL objects.

Finally we have investigated the possibility of explaining the difference between the XLFs of the two classes of objects in terms of an additional beamed radio-linked component producing X-rays. This component, intrinsically weak, becomes dominant when the direction of the jet with which it is associated is oriented close to the line of sight. Using the relation Log$L_x = 0.13\times$Log$(L_{xb}/L_{xu}) + 27.52$ we have calculated the unbeamed X-ray luminosity for each RL AGN in our sample. We find that the shape of the XLFs for RQ and RL AGN is the same if for the latter we use only the unbeamed component.

This results supports the two component scenario for quasar X-ray emission with the radio-linked component in RL AGN being orientation-dependent.

lished *Einstein* X-ray observations exists. In Browne and Murphy (1987) the monochromatic X-ray luminosity at 2 keV are in W Hz$^{-1}$ with 19.14≤ Log$L_x$ ≤22.13. Kembhavi used the same sample, with the same interval of Log$L_x$ but he assumed that the luminosities were expressed in erg s$^{-1}$ Hz$^{-1}$. There is a clear mistake in the units used by Kembhavi (1993).

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## REFERENCES

Avni Y., Bachall J.N., 1980, ApJ, 235, 694.
Blandford R.D, and Königl A., 1979, ApJ, 232, 34.
Boroson T. A., 1989, ApJ, 343, L9.
Boyle B.J., Shanks T., Peterson B.A., 1988, MNRAS, 238, 957.
Boyle B.J., Griffiths R.E., Shanks T., Stewart G.C., and Georgantopoulos I., 1993, MNRAS, 260, 49.
Boyle B.J., McMahon R.G., Wilkes B.J. and Elvis M., 1995, MNRAS, 272, 462
Browne I.W.A. and Murphy D.W., 1987, MNRAS, 226, 601.
Browne I.W.A. and Perley R.A., 1986, MNRAS, 222, 149.
Canizares C.R., and White J.L., 1989, ApJ, 339, 27.
Ciliegi et al., 1995, in preparation.
Della Ceca R. Maccacaro T., Gioia I.M., Wolter A. and Stocke J.T, 1992, ApJ, 389, 491.
Della Ceca R., Zamorani G., Maccacaro T., Wolter A., Griffiths R., Stocke J.T., and Setti G., 1994, ApJ, 430, 533.
Elvis M. et al., 1994, ApJSS, 95, 1.
Evans, 1988, PhD Thesis, Univ. of Cambridge.
Fiore F., Elvis M., Mc Dowell J., Siemiginowska A. and Wilkes B.J., 1994, ApJ, 431, 515.
Ghisellini G., Padovani P., Celotti A., and Maraschi L., 1993, ApJ, 407, 65.
Gioia I.M., Maccacaro T., Schild R.E., Wolter A., Stocke J.T., Morris S.L., and Henry J.P., 1990, ApJS, 72, 567.
Kellermann K.I., Sramek R., Schmidt M., Shaffer D.B., and Green R.F., 1989, AJ, 98, 1195.
Kembhavi A.K., Feigelson E.D. and Singh K.P., 1986, MNRAS, 220, 51.
Kembhavi A.K. 1993, MNRAS, 264, 683.
Lawson A.J., Turner M.J.L., Williams O.R., Stewart G.C., and Saxton R.D., 1992, MNRAS, 259, 743.
Maccacaro T., Gioia I.M., Wolter A., Zamorani G., and Stocke J.T., 1988, ApJ, 326, 680.
McMahon et al., 1995, in preparation.
Marshall H.L., Avni Y., Braccesi A., Hucra J., Tananbaum H., Zamorani G., Zitelli V., 1984, ApJ, 283, 50
Murphy D.W., Browne I.W.A. and Perley R.A., 1993, MNRAS, 264, 298.
Padovani P., 1993, MNRAS, 263, 61.
Peacock J.A., 1985, MNRAS, 217, 601.
Perley R.A., 1982, AJ, 87, 859.
Press W.H., Teukolsky S.A., Vetterling W.T.and Flannery B.P., 1992, *Numerical Recipes, Second Edition*, Cambridge: Cambridge Univ. Press.
Schmidt M. and Green R.F., 1983, ApJ, 269, 352.
Shastri P., 1991, MNRAS, 249, 640.
Stocke J.T., Morris S.L., Gioia I.M., Maccacaro T., Schild R.E., Wolter A., Fleming T.A., and Henry J.P., 1991, ApJS, 76, 813.
Stocke J.T., Morris S.L., Weymann R.J., and Foltz C.B., 1992, ApJ, 396, 487.
Wilkes B.J. and Elvis M., 1987, ApJ, 323, 243.
Worrall D.M., Giommi P., Tananbaum H., Zamorani G., 1987, ApJ, 313, 596.
Zamorani G. et al., 1981, ApJ, 245, 357.

## Figure Captions

**Figure 1.** The X-ray to optical spectral index ($\alpha_{ox}$) plotted against the radio to optical spectral index ($\alpha_{ro}$). The dashed line represents the divison between radio-loud ($\alpha_{ro} \geq 0.35$) and radio-quiet ($\alpha_{ro} < 0.35$) objects.

**Figure 2.** The de-evolved X-ray luminosity function for RQ AGN (open symbols) and RL AGN (filled symbols). *Upper panel*: data from the EMSS sample (model A). *Lower panel*: data from EMSS + CRSS sample (model C)

**Figure 3.** Distribution of $\alpha_{ro}$ for the CRSS AGN (upper panel) and for CRSS + EMSS sample (lower panel). The radio detections are show as shaded histogram while the $5\sigma$ radio upper limits are show as solid histogram.

**Figure 4.** The de-evolved X-ray luminosity function for RQ AGN (open symbols) and RL AGN (filled symbols) for different values of the dividing point between RQ and RL populations. *Upper panel*: dividing point at $\alpha_{ro}$=0.20 assuming that all the sources with radio upper limit $\alpha_{ro} \geq$0.20 are RQ AGNs *Central panel*: dividing point at $\alpha_{ro}$=0.40 *Lower panel*: dividing point at $\alpha_{ro}$=0.50

**Figure 5.** Distribution of the CRSS and EMSS AGN in the $\alpha_{ro}$ - log $L_X$ plane. *Upper panel*: in this panel are show only the objects with a radio detection. The dotted lines represent $\alpha_{ro}$ = 0.20, 0.35, 0.40 and 0.50, the values used to descriminate between RQ and RL (see §4.2 for more details). *Lower panel*: Radio detections plus $5\sigma$ upper limits.

**Figure 6.** The de-evolved X-ray luminosity function for RQ AGN (open symbols) and RL AGN (filled symbols). For RL objects we used only the unbeamed X-ray luminosit obtained from the relation $\text{Log}L_x = 0.13 \times \text{Log}(L_{xb}/L_{xu}) + 27.52$ (see §4.3 for more details).